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Physics Beyond SM at RHIC with Polarized Protons

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Abstract. The capabilities of RHIC with polarized protons to test the Lorentz structure of electroweak interactions and also the properties of MSSM Higgs, should it be discovered, are discussed.

INTRODUCTION

RHIC-Spin experiment is about being started. It has the solid program³, mainly concentrated around the measurements of proton spin dependent structure functions. For the last years, few attempts have been undertaken to also evaluate RHIC-Spin capabilities for testing physics beyond the Standard Model (SM) [1–3]. Since the recent suggestion [4] on a considerable increase of RHIC luminosity in pp mode along with a sizeable energy increase, RHIC-Spin potential in this area became looking even more promising.

In this report, we update our earlier study [2] of RHIC-Spin capabilities to explore the Lorentz structure of electroweak interactions and also provide some estimates on whether Higgs sector could be reachable at RHIC. In our considerations, we assume $\sqrt{S} = 500$ GeV and the luminosity of $0.8 \text{ fb}^{-1}/\text{year}$ for RHIC before an upgrade (RHIC-500), and $\sqrt{S} = 650$ GeV and the luminosity of $\sim 20 \text{ fb}^{-1}/\text{year}$ for the after upgrade (RHIC-650).

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³) See plenary talk by N. Saito in this proceedings.

LORENTZ STRUCTURE OF QUARK ELECTROWEAK CURRENT

Lorentz structure of electroweak interactions had always been and remains to be the focus of many precise nuclear and particle physics experiments. Over the last few years, the first measurements of the proton's weak magnetism have been accomplished [5]. Much attention had also been paid to test the universality of the electroweak interactions, in general, and to evaluating electroweak dipole moments of quarks and leptons, in particular. The current experimental constraints to magnetic and electric dipole moments of quarks and leptons, except electrons and muons, are still quite far from the values, predicted in the SM. If any of these moments were found to be nonzero and above SM's expectations, this would be a clear signal of a new physics beyond SM [6,7].

The most stringent experimental constraints, applicable to all components of quark and τ -lepton dipole moments, come from the recent analyses [6,7] of electroweak data from high energy colliders. In these analyses, it has been assumed that theories beyond the SM, emerging at some characteristic energy scale above W/Z mass, have effects at low energies $E \leq M_{W,Z}$, and these effects can be taken into account by considering a Lagrangian that extends the SM Lagrangian, L_{SM} : $L = L_{SM} + L_{eff}$. To preserve the consistency of the low energy theory, it had also been assumed that L_{eff} is $SU(3) \otimes SU(2) \otimes U(1)$ gauge invariant. Phenomenologically, this extension is equivalent to an introduction of a tensor coupling of fermions to gauge bosons which had also been discussed in Refs. [8,2,3]:

$$L_{eff}^{charged} = \frac{g}{2\sqrt{2} \cdot \Lambda} \left\{ \bar{q}_d \sigma^{\mu\nu} (f_T^+ + f_T^- \gamma_5) q_u \partial_\nu W_\mu^- + \bar{q}_u \sigma^{\mu\nu} (f_T^{*+} - f_T^{*-} \gamma_5) q_d \partial_\nu W_\mu^+ \right\} \quad (1)$$

In Eq. (1), representing the charged-current part⁴ of L_{eff} , g is the electroweak coupling constant, Λ is the energy scale of the “full strength” tensor interactions, and the asterisk denotes the complex conjugate. The notations q_u and q_d are for the “upper” (u and c)⁵ and “lower” (d, s, b) quarks, respectively. The CP - and T -invariance of model (1) is broken if any or all “formfactors” f_T^\pm were complex⁶.

With the coupling (1), a number of prohibited in the SM spin asymmetries must show up in the annihilation of polarized $q\bar{q} \rightarrow W^\pm/Z^0/\gamma \rightarrow l\bar{l}$ [2,3]. For polarized proton collisions, particularly interesting would be single-spin asymmetries with transverse polarization, arising from the interference of SM's and tensor couplings, because: a) these asymmetries are strongly suppressed in SM and b) they are expected to have a good sensitivity to anomalous interactions due to quite strong correlations between the proton spin and polarizations of high- x valence quarks, that participated in gauge boson production [9]. The triple-vector correlations,

⁴) With omitted quadratic terms, proportional to $g^2 W_\mu W_\nu$; the neutral-current L_{eff} looks similarly.

⁵) t -quark is virtually not reachable at RHIC.

⁶) In this paper: $\gamma_5 = -i\gamma^0\gamma^1\gamma^2\gamma^3$ and $\sigma^{\mu\nu} = \frac{1}{2}(\gamma^\mu\gamma^\nu - \gamma^\nu\gamma^\mu)$.

$\propto(\mathbf{k} \cdot [\boldsymbol{\zeta}_q^\perp \times \mathbf{p}_q])$, give rise to the “left-right” asymmetry A_N , while nonzero “up-down” asymmetry A_T comes from P - and CP -violating⁷ two-vector correlations, $\propto(\boldsymbol{\zeta}_q^\perp \cdot \mathbf{k})$. In the formulae above, \mathbf{p}_q and $\boldsymbol{\zeta}_q^\perp$ are for the momentum and transverse polarization of an incident quark, and \mathbf{k} is the momentum of a final lepton. The respective asymmetries $\hat{a}_{N,T}$ in W^\pm production at the quark interaction level, integrated over the phase space of final leptons, would be as follows:

$$\hat{a}_N \simeq \frac{3\pi}{16} \cdot \frac{M_W}{\Lambda} \cdot \text{Re}\{f_T^+ \mp f_T^-\} / \left\{1 + \frac{M_W^2}{4\Lambda^2}(|f_T^+|^2 + |f_T^-|^2)\right\} \quad (2)$$

$$\hat{a}_T \simeq \frac{3\pi}{16} \cdot \frac{M_W}{\Lambda} \cdot \text{Im}\{f_T^- \mp f_T^+\} / \left\{1 + \frac{M_W^2}{4\Lambda^2}(|f_T^+|^2 + |f_T^-|^2)\right\} \quad (3)$$

Formulae (2,3) have been obtained, using the solutions of Ref. [2] and with the assumptions that, the SM part of $q\bar{q}W$ -interactions as well as the lepton coupling to W^\pm were purely V - A . The upper and lower signs correspond to W^+ and W^- productions, respectively.

TABLE 1. RHIC-Spin sensitivity to $q\bar{q}W$ tensor coupling. Constraints (2σ) in columns 2–3 are for the asymmetries at quark (\hat{a}) and proton ($A \simeq \hat{a}/2$ [9,3]) interaction levels. RHIC sensitivities (2σ) to $A_{N,T}$ are shown in columns 4–5, assuming a 70% proton beam polarization.

Constraints from Ref. [6]			RHIC sensitivity in (W^+/W^-) modes	
$(f_T^+ ^2 + f_T^- ^2) \cdot M_W^2/\Lambda^2$	$\hat{a}_{N,T}$	$A_{N,T}$	RHIC-500	RHIC-650
≤ 0.15	$\lesssim (20-30)\%$	$\lesssim (10-15)\%$	$\sim (1.5/3.0)\%$	$\sim (0.2/0.4)\%$

The experimental constraint on “formfactors” f_T^\pm in charged current $u \leftrightarrow d$ transitions, converted to the convenient for our goals representation, is shown in Table 1, along with the respective limits on spin asymmetries in $pp^\uparrow \rightarrow W^\pm + X \rightarrow \ell\bar{\ell} + X$ processes. These limits then are compared with the RHIC sensitivities to $A_{N,T}$. One can observe that the current limits on f_T in quark sector could be lowered by a factor of 5-10 at RHIC-500, and by almost an order of magnitude more after the upgrade to RHIC-650. And what is probably even more important, the real and imaginary parts of f_T^\pm could be constrained individually from four independent measurements of A_N and A_T in W^+ and W^- productions.

WILL HIGGS PHYSICS BE REACHABLE AT RHIC?

In the recent years, extensive efforts for cornering Higgs bosons resulted in the significantly shrunken area of the still allowed Higgs sector parameters. The actual discovery of Higgs particle(s) is expected to occur in not so remote future. Then, the focus will be shifted to studying their properties. Does RHIC with *polarized* protons have capabilities to contribute in this study?

⁷⁾ In this particular model for $L_{eff}^{charged}$.

The production cross section of Higgs strongly depends on the helicities of initial gluons and quarks. As a result, measurements of spin-correlations in polarized pp collisions may allow us, for example, to determine CP -parities of Higgs states. Potentially, an interference between Higgs production and other SM processes in collisions of polarized gluons and quarks can generate a number of interesting single- and double-spin asymmetries⁸, including those sensitive to CP -violation in Higgs sector. In some cases, the polarization may help to improve signal-to-background ratio compared to unpolarized particle collisions.

Currently, the data favor low mass Higgs, probably just around ~ 100 GeV, and for the Minimal Supersymmetric extension of the Standard Model (MSSM), the versions with large $\tan\beta \gtrsim 10$ seems as taking preferences⁹. Let's imagine for a moment that, just before RHIC-Spin upgrade, a neutral scalar¹⁰ has been discovered with the mass $M_h \sim 115$ -120 GeV, and its characteristics were consistent with the MSSM Higgs for $\tan\beta \simeq 30$. The estimated production cross section, σ_h , for such boson(s) at RHIC-650 would be ~ 0.5 pb with approximately equal contributions of $gg \rightarrow h$ and $q\bar{q} \rightarrow h$ subprocesses¹¹. For an integrated luminosity of 20 fb/year, one may expect a yield of $\sim 10^4$ h /year.

The main decay modes of low mass Higgs scalars are: $h \rightarrow b\bar{b}$ with the branching of $\sim 90\%$, and $h \rightarrow \tau^+\tau^-$ with the branching of ~ 8 -9%. At the early stage, both these modes have been determined as hardly be suitable for the Higgs searches. However, as it was pointed out in Ref. [13], $h \rightarrow \tau^+\tau^-$ decay might become useful "to provide confirming evidence for a signal found in other modes"¹². In this report, as a first step toward understanding the Higgs-at-RHIC problem, we will start with the evaluation of only these two modes with the highest branchings, keeping in mind of course, that future studies could reveal better ways for the Higgs sector exploration at RHIC¹³.

The main obstacle for using $b\bar{b}$ channel at hadron colliders is the large QCD background from $gg \rightarrow b\bar{b}$. At RHIC-650, the estimated with PYTHIA production cross section $\sigma_{QCD}^{b\bar{b}}$ for $b\bar{b}$ -pairs in the mass interval of $115 \times (1 \pm 10\%)$ GeV is $\gtrsim 10^3$ pb. Resulting from cross section estimates Higgs signal-to-background ratio, σ_h/σ_{QCD} , at $\lesssim 5 \cdot 10^{-4}$ does not seem too encouraging, particularly for studying Higgs properties. Potentially, an interference between $gg \xrightarrow{QCD} b\bar{b}$ and $gg \xrightarrow{h} b\bar{b}$ could improve this ratio up to $\sim \sqrt{\sigma_h/\sigma_{QCD}} \sim 10^{-2}$. Unfortunately, in the ultra-relativistic limit of massless b -quark, these two channels do not interfere. As a result, the actual interference term is additionally suppressed by a factor $m_b/M_h \sim 0.03$ -0.04, which brings it back to the same low level of $\lesssim 5 \cdot 10^{-4}$.

⁸⁾ Similar to the ones described, for example, in Refs. [10].

⁹⁾ See, for example, [11,12] and references therein.

¹⁰⁾ Or scalars; for large $\tan\beta$, the theory allows for all three MSSM neutral bosons, h^0 , H^0 and A^0 , to be sitting simultaneously in the mass region from ~ 100 to 130 GeV [12].

¹¹⁾ Notation h is used here as a generic name for either h^0 , H^0 or A^0 .

¹²⁾ See also Ref. [12], page 29 for the similar qualification.

¹³⁾ See, for example, J. F. Gunion and T. C. Yan, *Phys. Rev. Lett.*, **71** (1993) 488.

The background to $\tau^+\tau^-$ pairs from Higgs decays predominantly comes from the Drell-Yan process: $q\bar{q} \rightarrow \gamma/Z^0 \rightarrow \tau^+\tau^-$. For RHIC-650, PYTHIA estimates the Drell-Yan cross section for $\tau^+\tau^-$ at ~ 0.25 pb in the τ -pair mass interval of $115 \times (1 \pm 10\%)$ GeV. Taking into account $\sim 8\%$ branching of Higgs to $\tau^+\tau^-$, the signal-to-background ratio in this mode would be $\sim 15\%$. With the detection efficiency for high-mass τ -pairs at about 20%, the event rate in the mass interval above should be expected at $\sim 10^3$ τ -pairs/year. For this rate, $\sim 15\%$ excess of events due to Higgs decays should be detectable well above the statistical fluctuations. Then, for example the CP -parity of a detected Higgs boson could be determined by measuring the sign of the contributing to the cross section double-spin correlation ($\zeta_q^\perp \cdot \zeta_{\bar{q}}^\perp$) in collisions of transversely polarized protons. However, the statistics of just $\sim 10^2$ of $h \rightarrow \tau^+\tau^-$ decays/year may not be sufficient for measuring double-spin asymmetries. Unfortunately, we cannot count on potentially more sensitive single-spin ones which could arise from an interference of two competing $q\bar{q} \rightarrow \tau^+\tau^-$ channels. This interference will be vanishingly small because Drell-Yan pairs are mainly produced by light quarks, while the respective part of Higgs cross section will predominantly be due to $b\bar{b}$ -annihilation.

CONCLUSION

It has been shown that RHIC with polarized protons will have highly competitive capabilities for hunting anomalies in the Lorentz structure of electroweak interaction due to physics beyond SM.

The low-mass Higgs might be reachable at high luminosity RHIC-650, although finding appropriate modes to study polarization phenomena in Higgs sector will be a quite challenging task.

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